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Effect of Timber Cutting on Water Available for Stream Flow from a Lodgepole Pine Forest[1]

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INTRODUCTION

Wherever people have settled in the West, the availability of adequate supplies of water has been the limiting factor in economic development (*46*, pp. 330–461).[4] From the earliest pioneer days men have established and fought for claims to the use of water and have built up an intricate system of water development and water rights, so that now the available flow of almost every stream in arid sections has been legally appropriated for human use.

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[4] Italic numbers in parentheses refer to Literature Cited, p. 40.

With water from the forest-covered mountains which interlace its lands, the West has built a vigorous structure of thriving cities and productive farms. But now this development has almost reached its peak in many western areas, as the limit of available water supplies is approached. Some parts of the Southwest, in fact, have passed this limit; with water supplies inadequate to meet existing demands, underground water reserves are frequently being depleted to a serious extent.

These facts are evident to any westerner. He sees that ample supplies of usable water are a vital requirement for the welfare of all his western country. Thinking about this problem for his own region, he raises several questions: Just where does our water come from? Do we still have enough? If not, is there any means by which we can increase its quantity without lowering its quality?

The purpose of this bulletin is to discuss, in some detail, answers to these questions, at least for an important part of the central Rocky Mountain region:[5] the first two questions by analysis of known facts, and the third partly by appraisal of possible methods but chiefly by examining the results of research.

Source of Water Supplies

First, where does the water come from? Considerably more than half of the water originating in this region flows from the forested watersheds of the high Rocky Mountains. This mountainous zone, where almost every acre of forest has a major influence on water supplies, is the source of water which is used throughout much of the West. From the Continental Divide large streams carry their water in all directions: the Yellowstone and other upper Missouri River tributaries to the north, the Platte and Arkansas to the east, the Rio Grande to the south, and the Colorado River to the west. These streams yield an average of about 28 million acre-feet of water per year, of which over 7 million are consumed within the region; most of the rest is absorbed by human needs all through the arid Western States (*53*).

Need for Additional Supplies

Do we have enough water? No: even this great supply is not sufficient for present and future needs of the Western States. Already water deficiencies have caused substantial losses in agricultural production, and have inhibited the further development of industry in many western cities. Within the Rocky Mountain region itself, water supplies available to the densely populated areas east of the mountains are now almost completely utilized. Most of the larger cities of the region are located in this zone; and of a total of over 4½ million acres of irrigated land, more than 3 million acres lie in eastern-slope drainage basins. On some of these streams the demand for water is already so intense that even the highest flood discharges have been legally appropriated for irrigation use. In the North Platte basin, for example, existing

[5] Including Colorado, Wyoming east of the Continental Divide, and western Nebraska and South Dakota.

water rights exceed the highest recorded annual runoff (4 million acre-feet). And in eastern Colorado, expansion of irrigated agriculture has been so great that for over 20 years the average annual water supply has not met the demand.

Methods for Increasing Supplies

Finally, are there any methods by which we can increase our supplies of available water? Actually there may be two practical methods. One of these, the use of transmountain diversions, additional reservoirs, and related structures, is already providing a great contribution to the development of western water resources. The other, the planned management of watershed land and vegetation, is just now beginning to gain recognition as a potential source of larger and better-quality water supplies.

On the first of these two methods, millions of dollars have already been invested throughout the arid West; and the investment of many additional millions is planned for future years, so that every possible beneficial use may be made of available water supplies. To illustrate this kind of development, in the South Platte Valley alone there are almost 300 storage reservoirs and about 900 diversion dams large enough to be registered with the State engineer of Colorado. In the whole Rocky Mountain region there are almost 900 storage reservoirs, with a combined capacity of about 4½ million acre-feet of water. Several transmountain diversion systems such as the Moffat tunnel system are now in operation, bringing water from the western slope to the areas of high demand east of the mountains. Others, like the great and complex Big Thompson system, are under construction; and still more diversions are planned for the future.

Important as they are, these structures and water developments cannot do the whole job of making the greatest possible use of western water resources. They add greatly to the efficiency of water use, but they contribute nothing to the total yield of water from our mountain watersheds. Reservoirs and dams only regulate the rate of discharge, making water available when it is most seriously needed; and transmountain diversions merely shift water supplies from a zone of local abundance to one of local scarcity.

To supplement these measures—to help keep our reservoirs filled with water and free of silt, and to insure an ample supply of water for the populations on both sides of the mountains—it is essential that the forester handle his watersheds so as to provide a maximum supply of usable water. This is a major task of the watershed manager: to regulate the density of timber on forested watersheds so that consumption of water will not be excessive, and still to maintain the watersheds in productive condition, producing timber and other forest products as well as clear, usable water. We know that, through interception and transpiration, a dense, unmanaged forest may take a heavy toll of water from the snow and rain that fall upon it. On the other hand, it provides favorable conditions for the absorption and storage of water, for the reduction of flood discharges, and for the control of erosion. In some areas a forest-covered watershed may supply the largest possible yield of well-regulated, silt-free stream flow, even though the total volume of water is reduced by forest uses. Here reductions in vegetation would result in erosion and floods which might make a portion of the water yield unusable. In other areas, however, where vegetation is not so essential for watershed protection, the need for greater water supplies may often justify timber cutting of various kinds and intensities. Thus, where water yield is a dominant factor in the economy of a drainage basin, it becomes imperative for the land manager to learn whether vegetative consumption of water can be reduced by properly managed timber cutting, without damaging the forest's capacity to minimize floods and erosion. The solution of this problem is one of the principal aims of watershed-management research in the central Rocky Mountain region (*48*).

Purpose and Scope of Investigation

The purpose of the present investigation was to determine, for one important forest type in the central Rocky Mountains, the influence of an uncut forest and of several intensities of timber cutting on the amounts of precipitated water which can percolate through the soil mantle and become available for stream flow. More specifically, the object was to find out how much water passes through the canopy and root zone of an uncut forest, as compared with the amounts penetrating stands which were subjected to various intensities of timber cutting. As a direct corollary it was also desirable to observe any soil erosion and other effects on the local environment resulting from the timber-cutting operations.

Conducted on experimental plots, these investigations could not supply quantitative information on the effect of timber cutting on actual water yields. The observed effects must be further tested by stream-flow studies, in which approved timber-cutting methods are applied to water-producing areas. Such studies (already in operation) can test only one or two desirable cutting methods, and can be completed only after a period of 10 or more years; they are therefore outside the scope of this publication. In the meantime, these short-term and detailed studies on experimental plots can supply definite information on how timber cutting in a variety of intensities affects the amounts of water which are available for stream flow, and can provide a sound introduction to the planning of watershed management.

Selection of Forest Type and Area

It was necessary to confine this experiment to a single important forest type. The lodgepole pine type was selected, for it occupies a considerable part of the most important water-yielding zone in the Rocky Mountain region.[6] The lodgepole pine zone in this region covers about 3 million acres, almost equally divided between Colorado and Wyoming. It lies in a belt limited roughly by the 8,000-foot and 11,000-foot contour lines—just below and overlapping the spruce-fir type, which extends from about 10,000 feet to timber line at about 11,500 to 12,000 feet. The average yield per acre being

[6] Research has also been started in the Engelmann spruce-alpine fir type, which occupies the remainder of this zone.

at least one acre-foot of water, the average annual yield from this lodgepole pine area is estimated to be about 3 million acre-feet, worth about 8 million dollars for irrigation alone.

The study area selected is near the Continental Divide in Colorado, in the headwaters of the Fraser River, a drainage basin which is tributary to the Colorado River and the Colorado-Big Thompson and Moffat transmountain diversions. Thus, it not only is typical of the lodgepole pine and spruce-fir types, but also is located in one of the most important watersheds of the region.

THE PROBLEM

As a background for the development of methods for watershed management in the lodgepole pine type, it is desirable first to outline the major factors that need to be examined. In addition, it will be helpful to review the fund of knowledge which earlier studies have made available on the general problem.

CHARACTERISTICS OF WATER YIELD IN THE LODGEPOLE PINE TYPE

Judging from the records of stream-gaging stations in Colorado and Wyoming, the annual water yield of watersheds in the lodgepole pine zone ranges from about 9 to about 16 inches of water, with an average of at least 12 inches. In the Fraser River Basin, measured yields vary between 12 and 16 inches, probably because these areas include portions of the spruce-fir type and some alpine grassland. On the Fraser Experimental Forest, the annual yield of one controlled watershed has averaged 12.1 inches of water; almost 50 percent of the annual precipitation.

Of this 12-inch average yield, about 70 percent has been derived directly from melting snow between the first of April and the end of June each year. Only 5 percent has come directly from summer rains, and the remaining 25 percent from stable, perennial baseflow. Since, however, even the base-flow must have been derived largely, though indirectly, from snow, we can safely say that about 85 to 90 percent of the total annual yield has come directly or indirectly from snow.

THE WATER CYCLE AS AFFECTED BY THE FOREST

These figures show the general pattern of water yields in the lodgepole pine zone. In addition, some idea of how these yields are affected by the forest cover can be gained by looking in greater detail at the seasonal cycle of precipitation and runoff for a typical watershed in this forest type.

Each autumn, usually early in October, the first snows begin to fall; commonly in small, light storms. Settling on the forest canopy and passing through it onto relatively dry soil with its moisture depleted by the summer's transpiration and evaporation, most of this early snow is evaporated without accumulating moisture in the soil. Then, as autumn progresses into winter, a growing mass of snow is stored upon the ground. From every storm, however, the trees subtract a portion, holding it on their branches where, exposed in rounded stacks to wind and sun, much of the intercepted snow returns as vapor to the air. The rest becomes deeper and denser on the ground, until the longer days and warmer weather of early spring begin to speed its melting.

Up to now—in March or early April—the soil under the snow blanket is still quite dry; the water from any winter melting has remained in the snow, adding to its density. But soon the rate of discharge begins to rise; slowly at first, because the water from melting snow must wet the soil, replenishing the deficits caused by transpiration and evaporation during the preceding summer. After the soil is soaked, the percolating snow water reaches the stream at accelerated rates, building up flow to a peak in early June. Yet even now not all the snow can melt and enter the soil, for some is vaporized, especially where the high spring sun can penetrate the forest canopy. And even at the peak of melting in this zone, practically no water appears as surface runoff from the forested slopes; it all goes through the porous soil to reach the stream.

When the snow is gone, the flow declines, shaping a hydrograph which drops in a long and flattening curve on which the summer storms place minor peaks, formed by rain that falls directly into the stream and upon the wet soil of the canyon floor. Throughout this period, rain on the timber-covered hillsides adds nothing directly to the stream; after a fraction of each storm has been subtracted by interception, the rest serves only to offset in part the constant loss of water by transpiration and evaporation from the upper layers of soil. Even the stream itself is depleted by transpiration, for the stream-bank vegetation can draw its water rapidly and directly from the channel and from the adjacent ground-water table. Hence the declining curve of summer flow is broken on sunny days by a noticeable decrease in discharge, reaching its lowest point each afternoon and returning to the normal curve at night when, with temperatures close to freezing, practically no transpiration occurs.

Finally, in autumn and throughout the winter the stream maintains a minimum and almost constant flow, issuing from deep, perennial springs and unaffected by the winter storms.

The Components of Water Yield

Reasoning from the facts stated above, we can conveniently divide the annual cycle of water supply and consumption into a series of components, each of which can be sampled in a quantitative manner. If we start in the early spring and consider them in chronological sequence, the first of these components is the amount of water present on the ground in snow, before any appreciable amount of water has entered the soil beneath. This quantity integrates the joint effects of canopy interception and evaporation during the preceding winter; and it provides an initial figure on the amount of water available for stream flow, to which must be added (algebraically) the subsequent precipitation and losses throughout the year.

A second component is the amount of precipitation that passes through the forest canopy after the initial snow surveys and before the end of June. Falling largely on snow and wet soil, this precipitation is very likely to reach the water table and become directly available to stream flow. Because it occurs largely as snow and is accompanied by cold, cloudy weather, it also serves to prolong the period of snow-melt.

Tending to offset the addition of water by spring precipitation is a third component, evaporation of the stored snow, which is affected by the relative exposure of snow surfaces to sun and wind.

All three of these phenomena help determine the length of time required for the stored snow to disappear each spring. This period of snow-melt is of decided interest because it is associated with the rate at which stream flow leaves the watershed.

After the snow is gone and water tables have somewhat receded —about the end of June—later rains fall on relatively dry soil and ordinarily in small storms, so that they can hardly be expected to supply water directly to the stream. Still, this rainfall must be considered as a fourth component because, by adding moisture to the soil, it may affect its dryness in the autumn, before the winter snows begin to fall again. Associated with the net amount of summer rain is stem flow—water which trickles to the ground along the trunks of trees, after being intercepted by their crowns. If large in quantity, this minor component must be added to net precipitation to show the real net amount of water passing through the forest canopy.

In autumn, just before the early snows, one more component must be measured: the relative dryness of the soil, which expresses the joint effects of net rainfall, evaporation, and transpiration throughout the summer season. Expressed as a deficit below the capacity of the soil to hold moisture against gravity, this component tells also how much water from melting snow will be needed to refill the soil during the following spring, before additional water can reach the stream.

Taken together, these several components express all of the important increments and losses of water in the forest; they trace the course of rain and snow from the forest canopy into the soil, beyond the reach of forest roots. Looking at each component separately, we can see that each may be affected by timber cutting. Through reductions of canopy density, snow storage and net rainfall may be increased and transpiration losses reduced. Through greater exposure of the ground to sun, wind, and rain, evaporation from the snow and soil may be increased and melting rates accelerated. The algebraic sum of all these influences—whether negative or positive—should express the principal influences of timber cutting on the amounts of precipitated water which become available for stream flow.

Aside from its effects on the water-yield components, timber cutting may have other effects which must also be considered. If it is too heavy soil conditions may deteriorate through oxidation of forest litter and humus, resulting in lowered capacities of the soil for infiltration and percolation of water. This condition, combined with rapid melting of snow and decreased interception, may cause flashy stream runoff and accelerated soil erosion. Also, if timber cutting is improperly planned, the opening of the stand may cause windthrow or other damages, with consequent loss of timber production.

EARLIER APPROACHES TO THE PROBLEM

The influence of vegetation on stream flow has occupied an ever-increasing amount of attention from investigators for the past century or more. Most of the early work pertaining to this problem was thoroughly summarized in 1912 by Zon (*56*). In compiling these data, Zon distinguishes between investigations involving the study of stream flow from watershed areas, which he classifies as the hydrometric method; and the determination of the amounts of water available for stream flow by a synthesis of individually measured factors, or the physical method.

THE HYDROMETRIC METHOD.—This type of investigation is exemplified by the famous Emmenthal watershed study conducted in Switzerland since 1890, which has shown fruitful results in evaluating the influence of forest cover on stream flow under Swiss climatic conditions (*9, 10, 18*). Other hydrometric investigations of general interest have been established by the Forest Service, Soil Conservation Service, and others. Since 1912 the Intermountain Forest and Range Experiment Station has been measuring surface runoff and erosion from two small watershed areas in the head of Ephraim Canyon, Utah (*19*), with results which show conclusively that both runoff and erosion have been increased by the removal of herbaceous vegetation. More recently the Forest Service has developed a large-scale experiment for measurement of the influence of chaparral cover on stream flow and erosion in southern California (*32*), and another intensive study on the Coweeta Experimental Forest in North Carolina (*26, 27*). On a smaller scale, watershed experiments have also been started at other Forest Service research centers, including two in the central Rocky Mountains (*48*), and, along with a number of other investigations in soil and moisture conservation, similar work has been undertaken by the Soil Conservation Service at the Coshocton Experiment Station in Ohio (*38*).

In the western United States the relation of vegetation to stream flow has been the subject of much discussion, and is well analyzed by Leavitt (*33*), who discusses the three main problems: Water supply, erosion, and flood control. He recognizes the fact that in many areas water is the most important resource of forest and range lands, and that satisfactory conditions for water yield may require the modification of vegetation by timber cutting and grazing. Kittredge (*29*) points out that the need for increased water supplies may require forest management in which the object is to obtain a cover of trees with minimum foliage and transpiration, and to maintain the trees at minimum sizes and densities compatible with protection of the soil. Both authors emphasize the complexity of the problem.

The need for investigation of the relation of forests to stream flow in the West was recognized in the early part of this century by the Forest Service, and accordingly in 1910 the Wagon Wheel Gap watershed study was established in cooperation with the Weather Bureau (*5*). This study was rather comprehensive and particularly applicable to the present work because of its location in southern Colorado. In essence, the stream flow from two watersheds, each slightly larger than 200 acres, was measured for a period of 8 years. At the end of this period one watershed was "denuded" by removing practically all of the woody vegetation, after which the records of stream flow, precipitation, and other factors were continued for another 7 years. The effects of this seemingly severe treatment were not very pronounced, perhaps because both watersheds were rather thinly forested with aspen, Douglas-fir, and spruce before treatment; and because the aspen sprouted after denudation and rapidly restored the cover. During the first 3 years after treatment, however, it was found that the total annual yield of water was increased 17 percent by the removal of all the timber on the treated watershed. This gain dropped to an average of 15 percent over the whole 7-year period after treatment, probably because of the rapid sprouting of an aspen cover. The increase in flow was greatest in spring periods, but an excess was maintained throughout the drier summer months. The soil removed from the treated watershed by erosion averaged only 1.3 cubic yards per year.

In discussing the results, the authors suggested that increases in stream flow were largely due to decreased interception by tree crowns on the treated watershed. Although interception and other individual factors contributing to moisture depletion were not measured, it was inductively reasoned that water losses due to evaporation and transpiration added up to approximately equal quantities for both treated and untreated watersheds.

Among the more recent watershed investigations, the Forest Service experiments in North Carolina have shown striking effects of the removal of vegetation upon stream flow from watersheds in a "superhumid" climate. To quote from a recent statement (*24*):

> On a 40-acre watershed all woody vegetation was cut in the winter of 1939-40. Great care was taken to prevent disturbance to the surface-soil, no logs were removed from the area and all slash and brush were cut to lie close to the ground and evenly scattered. Natural regrowth has been allowed. A 33-acre drainage-area was cut-over in a similar manner in 1940-41 but new growth was cut in the growing seasons of 1941 and 1942. . . . In the first year after treatment, runoff was increased by almost 17 inches on both watersheds. In the second year, runoff was increased 9½ inches on the watershed where natural growth was allowed and 13 inches where the sprouts were cut. The increase in runoff is a result of the higher soil-moisture on the treated watersheds which causes a larger proportion of rainfall to be added to ground-water storage.

THE PHYSICAL METHOD.—Because of the inflexibility and long-term nature of watershed studies, the hydrometric method requires many years before final experimental results become available; and even then they may be of only local application. Hence a relatively large amount of effort has been devoted to the less direct, but quicker physical method, in which individual factors are measured to show how each is affected by vegetation. Since this method lends itself more readily to experimentation, a volume of data has been accumulated on the influence of vegetation on factors such as the storage and melting of snow, rainfall interception, evaporation, and soil moisture.

Of these factors, perhaps the accumulation and melting of snow have received the most widespread attention because of their great and direct influence on water yields from mountain areas. The engineer, the water user, and others interested in water yields have gone far in the development of instruments and techniques for sampling stored snow and for making forecasts of stream flow. The forester, on the other hand, with a somewhat different interest in water yields, has directed his attention primarily toward the influence of vegetation, especially forest cover, on the accumulation and melting of snow. As examples, early work by Griffin in the Cascade Mountains (*21*), and by Jaenicke and Foerster in the Southwest (*28*), showed that less snow was accumulated in the forest than in the open at the beginning of the melting season, but that it remained longer under the forest. Griffin's work in Douglas-fir was later substantiated by Meagher (*35*), who found that in cut-over forests the original blanket of snow melted in 1 week, while under old growth the melting of snow was evenly distributed over a 4-week period.

In Idaho, Connaughton studied rather intensively the accumulation and rate of melting of snow under different conditions encountered in a ponderosa pine forest (*14, 15*). He concluded that as much as 25 percent of the annual fall of snow could be intercepted and dissipated by mature tree crowns, and that the rate of melting could be retarded as much as 10 days by a forest cover.

Evaporation from a snow surface is an elusive factor, difficult to measure quantitatively. Some of the first measurements were attempted in Lapland by Rolf (*39*), who used shallow trays filled with snow which he weighed after a given period of exposure to determine evaporation and condensation. Baker (*2*), using somewhat the same technique in his work on the Wasatch Plateau in Utah, estimated that about 3 inches of moisture was lost by evaporation from a snow surface during one winter season. These results and those of other investigators employing similar empirical methods have been summarized by Clyde (*13*), and Kittredge (*29, 30*).

In recent work at Arlington, Va., Thornthwaite and Holzman approached the problem of evaporation by an indirect method in which they calculated evaporation, or condensation, from gradients of moisture concentration and wind movement directly above the land surface (*45*). In these investigations they found a marked suppression of evaporation during periods of snow cover. This they attributed to reduced turbulence above the relatively smooth snow surface, although they suggested that moisture losses by evaporation from a snow field may be larger when suitable atmospheric conditions prevail.

Important losses of rainfall as well as snow have been found to result from tree-crown interception. Early investigations of this factor have been summarized by Burger (*11*) and Horton (*25*). In addition they describe their own results; Horton's, obtained in New York State, indicate that net rainfall under individual trees of various species ranged from none for storms below 0.02 to 0.07 inch, up to about 75 percent of the total precipitation in storms of long duration.

More recently net rainfall has been studied under stands of jack pine (*36*), mixed oak, pine, and gum (*55*), Canary Island pine (*31*), Douglas-fir (*1*), chaparral and ponderosa pine in California (*40*), South African poplar (*47*), and other kinds of forest cover (*7, 34*). Over this considerable range of forest types and climates, net rainfall varied from 66 percent of the total precipitation under a Douglas-fir forest, up to 97 percent under a leafless stand of poplar.

In most cases the above-mentioned data on rainfall penetration include that which reached the ground by flowing down tree stems. Horton's early work (*25*) gave stem-flow values between 1 and 5 percent of the gross rainfall, and more stem flow was derived from broadleaved than from coniferous trees. In Kittredge's study of Canary Island pine, stem flow was about 1 percent of the total precipitation (*31*). In contrast, stem flow from the poplar trees used in Wicht's interception study (*47*) was 6 percent from trees in leaf and about 15 percent from bare trees. Finally, stem flow in ponderosa pine stands in California varied from 2 to 5 percent of the total annual precipitation, while in chaparral stands it averaged from 15 to 20 percent (*40*). The results of various studies have differed considerably; since stem flow varies with storm size, however, these differences may be due in considerable part to variations in the average volume and duration of rains, as well as to causes associated with vegetation.

A number of experiments have been made in the United States and Europe on the general influence of forest cover upon soil moisture and ground water. The more significant of the European results are well summarized by Halden (*22*). In general, these investigations resulted in rather comparable conclusions: that a heavy forest stand tends to lower the ground-water table and dry out the soil.

Of the several American studies, soil-moisture measurements by Bates (*3, 4*) at the Fremont Experiment Station and at Wagon Wheel Gap are the only data known to have been taken in the central Rocky Mountains, and these were not designed to show soil-moisture losses on an areal basis. Lunt (*34*), working in New England, found that isolated forest trees seemed to exert a definite influence in drying out the soil immediately under and close to each tree. According to Bauer (*6*), chaparral in the Santa Monica Mountains reduced soil moisture to values below the wilting point in a seasonal depletion curve which started in February and reached its lowest point in the autumn of each year. Working in chaparral types of central and southern California, Rowe (*40*) observed that losses by transpiration and evaporation of the water stored in the soil at the end of the rainy season were not materially affected by annual burning, grazing, or other manipulation of the plant cover.

In describing recent work in California orchards, Hendrickson (*23*) discusses the losses of soil moisture by transpiration and describes methods of study which are applicable to the present problem in forest soils. To determine soil-moisture deficiencies taking place during the growing season he obtained samples just after spring rains when the soil was at or near field capacity, and again at the end of the growing season, just before the onset of fall rains. In this work he found good agreement between the moisture equivalents of his soils and the field-capacity measurements. Browning (*8*), on the other hand, found that field capacity and moisture equivalent were approximately the same only for soils with a moisture equivalent of about 21 percent.

Although considerable attention has been given to each of the general factors—snow accumulation, evaporation and melting, interception, stem flow and transpiration of precipitation in forested watersheds—relatively few attempts have been made to combine these factors, principally because the individual factors were studied separately and under different conditions. From a theoretical standpoint, however, Zon (*56*) and Kittredge (*30*) have drawn together these components into a unified picture of the water cycle with relation to vegetative cover. Their chief objective was to show that a change in vegetation which affected any one of these elements would in turn affect the character of surface runoff and stream flow.

In general we can conclude from these varied investigations that a forest cover consumes substantial quantities of water through transpiration and interception; and it seems possible that these uses of water may be reduced by thinning the forest canopy.

EXPERIMENTAL AREA AND METHODS

THE AREA

Together with related investigations in watershed and timber management, these experiments were conducted on the Fraser Experimental Forest, located within the headwaters basin of the Colorado River near Fraser, Colo.

Here the climate and weather conditions are typical of the lodgepole pine zone, with long winters and short, cool summers. The annual precipitation on the study area has averaged about 24.5 inches, occurring largely as snow. Rainfall during the snow-free period (June through September) has ranged from about 3 to more than 10 inches. In this summer period the intermittent rainstorms are ordinarily gentle and light, averaging about 0.25 inch and seldom exceeding 1 inch. Growing seasons are comparatively short: conifer buds begin to open in June, and by the end of September most plant growth apparently stops. Throughout the year winds are generally light, especially during periods of rain and snow. At intervals averaging perhaps 5 years, however, winds of the foehn type may reach gale velocity, causing heavy windthrow of trees in exposed locations. In general the winds come from the west or southwest, though their local direction may be strongly influenced by variations in topography.

The study area lies in a small and rugged watershed, at elevations between 9,150 and 9,700 feet above sea level. The slopes of this mountain valley are variable in pitch, in places rising at angles as high as 45° from a gently sloping, V-shaped floor. While the stream runs generally north, the flank exposures vary from north to southwest and southeast.

In all of this area the soils are shallow and rocky, though ranging in type from clay loam in swales and depressions to coarse, gravelly loam on exposed ridges. The depth of the soil mantle above fractured parent material varies in general from 12 to 24 inches. As in other mountain soils, a poorly defined profile has been developed below a shallow surface layer of organic litter and humus material; and the soil breaks with little transition into the underlying rock. This parent material is metamorphic—mainly gneisses and micaceous schists—with occasional outcropping dikes of igneous origin.

The Experimental Plots

Scattered over the study area on a variety of slopes and exposures, 20 harvest-cutting plots were established in 1938 for silvicultural as well as watershed-management research. Each plot is 5 acres in size and is surrounded by a 3-acre isolation strip. The forest cover is mature lodgepole pine (*Pinus contorta* var. *latifolia*) (fig. 1), intermixed with Engelmann spruce (*Picea engel-*

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FIGURE 1.—A stand of mature lodgepole pine as it appeared before cutting treatments were applied.

manni) and alpine fir (*Abies lasiocarpa*) on moist sites. The timber stand contains 300 to 400 trees larger than 3½ inches in diameter (at breast height) per acre. From the smallest measured diameter (3.6 inches) the trees range in size up to an average maximum of 22 inches. The shortest of these trees average 35 feet in height, and the tallest about 80 to 85 feet; a few valley-bottom trees reach heights of 100 feet or more. Before cutting, the stand of merchantable timber—trees larger than 9.5 inches in diameter—had an average volume of about 12,000 board feet per acre; on individual plots, however, volume ranged from 7,600 to 17,000 board feet per acre. Beneath the forest canopy is a very sparse understory of pine and fir seedlings and saplings, together with scattered quaking aspen (*Populus tremuloides*) and shrubs—largely russet buffaloberry (*Shepherdia canadensis*). Practically no herbaceous vegetation is to be found, except along stream banks.

Plan of the Experiment

Five of the 20 plots were apportioned to each of 4 randomized blocks (figs. 2 and 3). In each block 4 plots were assigned, at random, different major timber-cutting treatments and the remaining plot was left uncut. This experimental design was intended to serve a threefold purpose: (1) Through the assignment of all 5 treatments to each of 4 relatively homogeneous areas, to reduce any uncontrolled variation that might affect the observed results of timber-cutting treatments; (2) through randomization, to give each treatment an equal chance to express its influence on factors associated with water yield; and (3) through the use of blocks that represent a variety of environmental conditions, to provide a reasonably

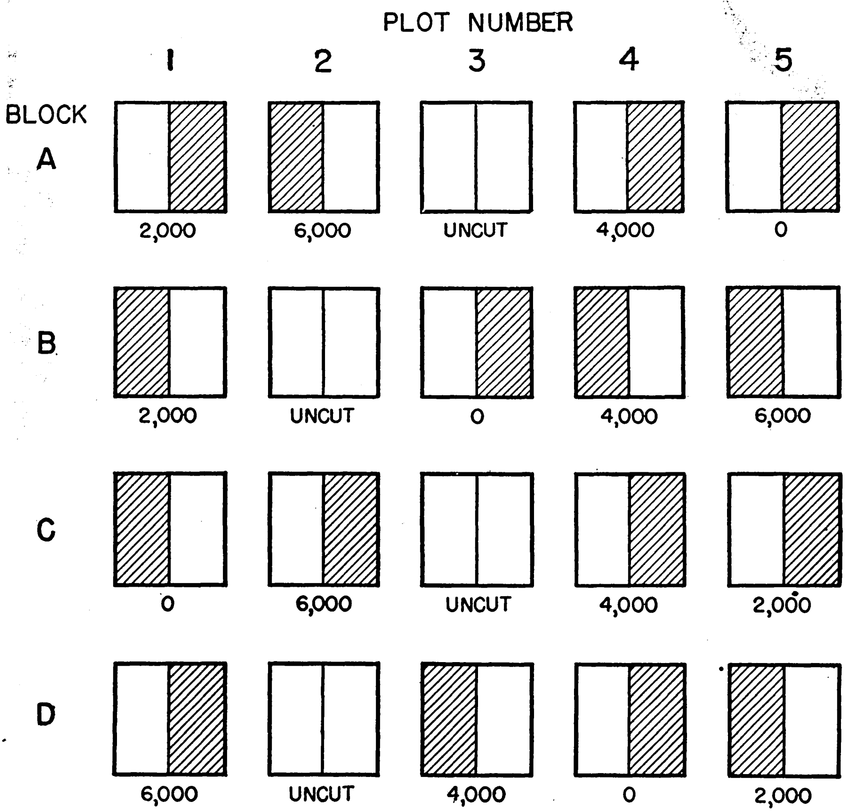

FIGURE 2.—Distribution of treatments, in four randomized blocks. Figures under plot diagrams signify merchantable reserve stand per acre in board feet. Hatching signifies timber-stand improvement.

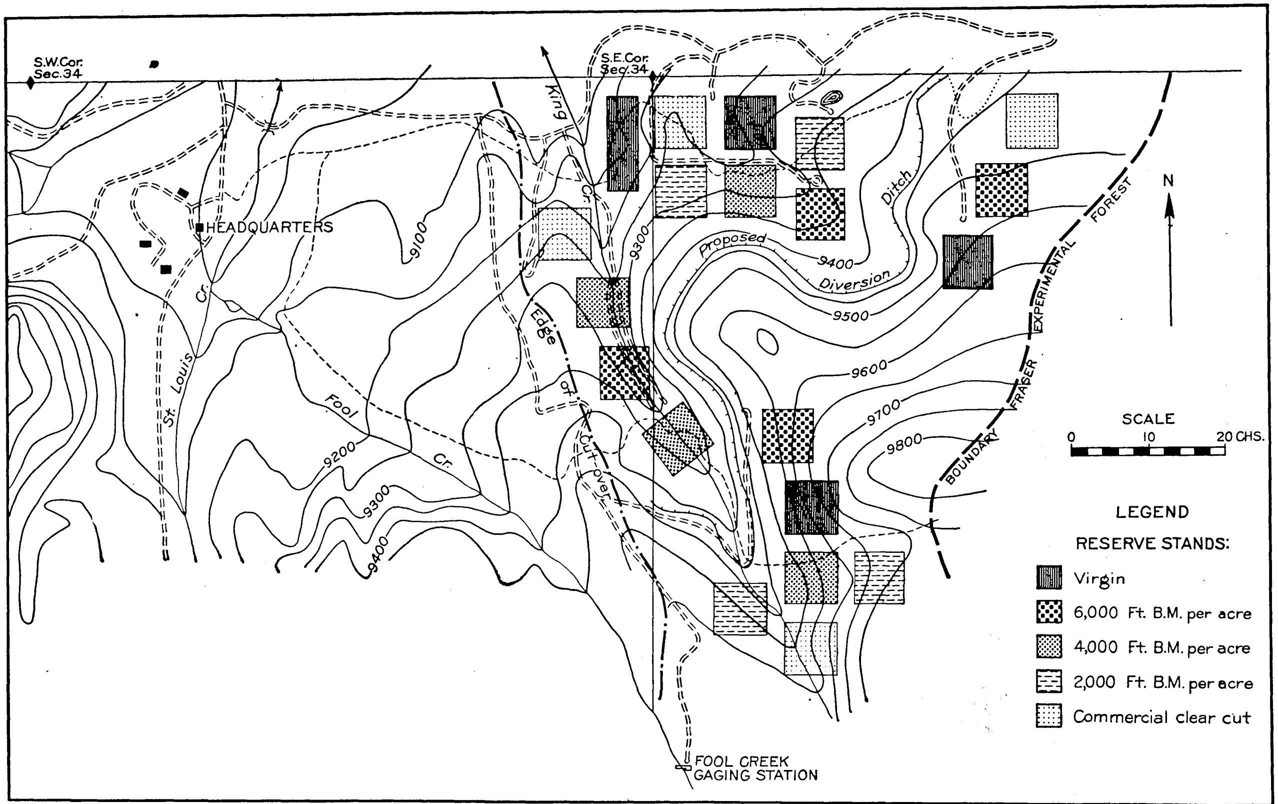

FIGURE 3.—Arrangement of the lodgepole pine harvest-cut ting plots used for the hydrologic experiment reported in this publication.

representative sample of the various conditions which exist in the lodgepole pine type. Since the experiment was necessarily confined to a single general area, the last of these objectives could be attained only within very definite limits.

In a timber-cutting operation applied to the plots in 1940, all trees larger than 9.5 inches in diameter were removed from one plot in each block; the other 3 cut-over plots were left with 2,000, 4,000, and 6,000 board feet of merchantable trees per acre. Because smaller trees were not cut, even the most severe cutting left a residual stand to provide partial cover and to protect the soil.

F-406364

FIGURE 4.—Cut-over plots in mature lodgepole pine. In foreground is a 2,000-board-foot reserve stand; in left background an uncut area.

After the heaviest cutting this stand contained, on the average, 147 trees larger than 3.5 inches in diameter, or about 38 percent of the average total number on the uncut plots (382 trees). The other treatments left an average of 206 trees in the 2,000-board-foot reserve stand (fig. 4), and 181 and 223 trees in the 4,000- and 6,000-foot stands, respectively. Because of original variations in the forest, these figures are not constant from plot to plot, nor even from acre to acre; one acre may be actually clear-cut, while another contains a fairly dense residual stand.

It is noteworthy that this cutting operation was conducted as a Forest Service timber sale, planned and supervised by the station's division of timber management. In all, approximately 125 acres of timberland were cut over, yielding a total of about 750 thousand board feet of salable lumber. At ordinary stumpage rates, this kind of sale provides a cash return of about $20 per acre in stumpage price alone, not counting the income to the private operator who cut the timber. Thus, in lodgepole pine as in other merchantable forest types, the cost of removing the timber does not have to be charged against any water-yield benefits. Instead, the cash return from the cutting operation may be made a part of the capital value of the watershed land.

In this particular operation the trees were felled, lopped, and cut into logs by hand. The resulting slash was lopped and scattered on one-half of each plot, and swamper-burned on the other half. All merchantable logs were skidded off the plots with horses (fig. 5), decked at the plot boundary (fig. 6), and removed by truck to the sawmill (fig. 7).

F-397904

FIGURE 5.—Logs were removed from the plots by horse skidding.

As a minor treatment superimposed upon the major timber-cutting treatments, undesirable trees within the diameter range from 3.6 through 9.5 inches were removed from one-half of each cut-over plot for the purpose of stand improvement. The number of trees which were taken ranged from 29 to 116 per acre on individual plots, and averaged 56 per acre. They included crooked and malformed individuals and trees containing rot or possessing small crowns and poor growing capacity.

METHODS OF INVESTIGATION

PRETREATMENT OBSERVATIONS.—Starting in the spring of 1938, 2 years before the plots were cut over, data were obtained on snow storage, melting rates, and net summer precipitation under the uncut forest. The primary object of these measurements was to

F-397901

FIGURE 6.—After removal from the plots, the logs were piled in decks.

F-397900

FIGURE 7.—From the log decks, the logs were hauled to the sawmill by trucks.

find out whether the measured factors varied markedly with natural variations in stand density, so as to obtain a preliminary estimate of the probable effect of timber cutting (*52*). A secondary object was to provide an estimate of past performance for these factors: to find out how greatly they varied from plot to plot before treatment, because of inherent variations in exposure, stand density, and similar conditions. If such variations were present also after treatment, they would naturally contribute to the apparent effects of timber cutting on each plot; and the isolation and removal of this extraneous contribution would add materially to the precision of experimental findings.

POST-TREATMENT OBSERVATIONS.—After the plots were treated, data were obtained over a period of 4 years (1941 to 1944, inclusive) on all important water-cycle components associated with the effect of timber cutting on water available for stream flow. In the measurement of these components, records were taken during the first 3 years on initial snow storage and melting rates and on autumn soil-moisture deficits, because of their importance in the water-yield picture. In addition the soil-moisture records were continued for a fourth year, because the effect of timber cutting on this one factor varied enough from year to year to make desirable a more stable estimate of average treatment effects. Net rainfall (as compared with snow storage) is of relatively minor importance in providing water for stream flow, and we found that the effect of timber cutting on this component remained remarkably constant. Hence only two seasons' records of net rainfall were obtained; enough to ascertain these effects and their constancy with satisfactory precision, and to provide a satisfactory regression equation showing the relation of net rainfall under each treatment to gross, or unintercepted, rainfall (*49*). This equation was applied to gross-rainfall data in order to calculate net rainfall for the periods when it was not actually sampled on the plots; thus supplying for each year a reasonably complete pattern of the disposal of precipitation under the forest, with maximum efficiency and without appreciable loss of precision in determining the net amounts of water that became available for stream flow under each timber-cutting treatment. As a part of the net-rainfall data stem flow was measured, but only for one season (1940), because this source of water was found to contribute a negligible quantity to the soil.

Of all the components measured, only snow evaporation could not be sampled directly on the plots because existing instruments were inadequate for the purpose. Thus it was necessary to measure this component at a stationary installation outside the area containing the plots, and, with 4 years' data from this source as a basis, to estimate rates of snow evaporation under the various cutting treatments.

The field methods employed for sampling and measuring all of these components are outlined below, in sufficient detail to indicate the character and thoroughness of the techniques used.

STORAGE AND MELTING OF SNOW.—In the study of snow storage and melting rates, 25 sampling points were established in 1938 on each of the 20 plots. These points, marked by 5-foot stakes calibrated in inches, were located at the intersections of rectangular coordinates spaced at intervals of 1.42 chains (93.7 feet).

Starting between March 15 and April 1 of each year—when the soil under the snow blanket on the plots was still dry and showed no signs of having received water from melting snow—a sample measurement of the depth and water content of snow was taken near each of the stakes, each week until all the snow had disappeared (fig. 8). In order to minimize the disturbing effect of

F-406363, F-406360

FIGURE 8.—The Utah snow sampler was used to take samples of snow depth and water content at 25 points on each plot.

storms which might occur during each weekly survey, a single block of five plots, all treated differently, was surveyed on each of 4 consecutive days. Thus storm effects were confined largely to the variation between blocks, rather than to that between treatments. The water-content samples were taken by means of a Utah snow sampler (*12*); at first with a standard spring balance, accurate to the nearest ounce, or inch of water; but after cutting treatment with a more precise balance, accurate to 0.1 ounce. For each sample, particular care was taken to obtain a complete core and to avoid locations which had been previously sampled or compacted by trampling. In this manner, an average water content for each half-plot was obtained each week throughout the melting period. Because of the mechanical distribution of the sampling points, no data were provided on sampling errors within each plot.

NET SPRING PRECIPITATION.—In order to obtain estimates of precipitation (mostly snow) which passed through the forest canopy and reached the soil or its snow mantle after the first snow survey, one nonrecording rain gage was employed on each of the 20 plots (ignoring, in this case, the minor treatment, as it was found to exert no measurable effect on net precipitation). For the first storm, the gage was assigned to a sampling point located by reference to a randomly drawn snow stake. Then the gage was moved to a newly randomized location for each successive reading, so that by the end of the snow-melting period a number of locations had been sampled in each plot. Since the incidence of snow falling on sloping surfaces may be considerably affected by wind, each gage was set up with the top of its funnel parallel to the contiguous snow surface (*20, 43, 44*). Then, in order to adjust the resulting catch to express the amount of water deposited on the horizontally projected land area, the observed precipitation for each storm was multiplied by the secant of the angle at which the gage was tilted during the storm. As a result of this sampling procedure, the observed total spring precipitation for each plot expressed the average influence of the crown canopy and of the various slopes and exposure upon the amount of water reaching the stored snow throughout the surface of the plot.

F-388710

FIGURE 9.—Snow evaporation was measured with the aid of a pan 500 square feet in area. (Shielded snow gages were installed later.)

SNOW EVAPORATION.—For the study of evaporation of water from snow, research has so far failed to devise a satisfactory instrument or method of use on sloping land surfaces under a forest cover (*2, 17, 39, 45*). Hence it was necessary to estimate this component from records obtained at a single large, stationary set of equipment installed in a small, level, open area surrounded by scattered lodgepole pine trees near the experimental forest headquarters (fig. 9). The portion of this equipment used for the present discussion consisted of a large circular pan, 500 square feet in area. From this pan, the water from melting snow was drained into collector cans in a nearby concrete pit. For the measurement of snow accumulation, records were kept continuously from the first autumn snow until the last snow had disappeared, by means of four shielded standard rain gages and one Friez intensity gage. Then, when the first snow began to melt, the water content and depth of the stored snow were sampled at 22 points in a ring surrounding the pan, and the mean water content was computed. By using snow depths observed at a set of 9 calibrated wands on the pan itself, this mean water content could be adjusted to the most probable value for water stored on the pan. Then an estimate of winter evaporation was obtained by subtracting the adjusted water content from the observed total winter precipitation. Similarly, total spring evaporation was calculated by adding the initial water content to the precipitation observed from the beginning to the end of snow-melt, and subtracting from this sum the total amount of runoff water (in inches) which was caught in the collector cans.

These measurements, of course, gave an estimate of snow evaporation at only one open area. In order to estimate the corresponding losses under the various densities of residual forest on the plots, evaporation was assumed to vary inversely with the density of forest cover, approaching zero under a completely closed canopy (in a hypothetical stand twice as dense as the uncut forest) and reaching the values observed at the snow-evaporation station as a maximum for open areas. With these assumptions and observed data as a basis the total yearly evaporation could be estimated from snow under each timber-cutting treatment.

F-397720

FIGURE 10.—Gross and net rainfall were collected in 8-inch rain gages.

NET SUMMER PRECIPITATION.—In the estimation of summer net rainfall reaching the soil on each plot after the snow had disappeared, 2 distinct sampling methods were used: one of simple plan, and the other a more efficient technique. In the first method, used for 2 summer seasons before the plots were cut over and for 1 season after treatment (*54*), 5 standard rain gages were assigned to each plot: one, for the estimation of gross rainfall, at the center of a randomly selected canopy opening large enough to eliminate canopy interception; and the other 4 located 1 chain to the north, east, south, and west of the center gage. These gages were left at the same sampling points for all 3 seasons. In the following season the other method was adopted (*37*, *49*). Twelve rain-gage locations were randomly selected in each of the 40 half plots. Then one pair of 8-inch standard rain gages (fig. 10) was assigned to each half-plot. For the first storm, one member of the pair was placed at 1 of the 12 selected points, for the measurement of net rainfall; the other gage, used for measuring gross rainfall, was placed in the center of the nearest available opening large enough to eliminate measurable interception effects—at least 30 feet in diameter. After each successive storm the "net" gage was moved to a new sampling point, and the "gross" gage placed in the nearest suitable opening. Thus a series of 12 storms gave one complete circuit of the randomized sampling points on each half-plot. For the succeeding 12 storms the same locations were used in a newly randomized sequence, so that after a total of 24 storms 2 pairs of readings were available for each of 12 locations on 40 half-plots—a total of 960 observations. As the locations were randomized over each half-plot the resulting data gave unbiased estimates of net and gross rainfall, expressed directly in inches per unit of plot area. In addition, regressions of net on gross rainfall made it possible to calculate net rainfall with considerable precision for periods when records of gross rainfall alone were available.

To measure stem flow, 108 trees were selected: 54 in a reserve stand of 6,000 board feet per acre, and 54 in an adjacent uncut stand (*54*). Each of these 2 sets was further subdivided into 3 species—lodgepole pine, Engelmann spruce, and alpine fir; and within each species 1 tree was drawn at random to represent each of 3 classes of crown density and quality, and each of 6 diameters, ranging by 2-inch intervals from 4 to 14 inches. On each of these trees the apparatus used to measure stem flow consisted of a lead collar fastened tightly around the trunk about 2½ to 3 feet above the ground, with a copper spout and rubber hose to conduct the water from the tree to a covered collector can (fig. 11).

F-385712

FIGURE 11.—Rain flowing down tree trunks was caught by lead collars and conducted into collector cans.

For purposes of analysis, the records of net precipitation during the spring, summer, and autumn were grouped into two periods. The first, extending from the time of initial snow surveys until June 30, included all precipitation which fell largely as snow or as mixed snow and rain, and which—falling on snow or wet soil—should pass directly into ground water. The second period, from July 1 until late in September, included only summer rains and ended just before the advent of autumn snow. Since these rains occurred during warm weather, and since records show that they exert a negligible influence on stream flow, it is assumed that all of the net precipitation during this second period was lost by evaporation and transpiration.

AUTUMN SOIL-MOISTURE DEFICITS.—Finally, completing the account of what happens to precipitation when it falls on the forest, records of autumn soil-moisture deficits were taken to determine how much water was required from melting snow to fill the soil to capacity (*50*). The object of these measurements was to obtain as efficiently as possible an estimate of the average deficit, expressed in inches of water, for each plot, major treatment, and year. For this study 10 sampling points were randomized on the unimproved half of each plot for each year's sampling, with a new set of points for each subsequent year: a total of 40 points per plot.

Each spring, within 2 to 4 days after the snow had disappeared and visible free water had left the soil at each sampling point, a complete series of soil samples was obtained. Because these were necessarily large in number, two practical expedients were required to minimize errors associated with moisture changes during the sampling period, and to reduce field labor to practical limits. First, the surface litter and about an inch of soil were scraped off before sampling to cut down the disturbing effects of any small rains that occurred during the week required for the sampling job. Then, each sample was taken to a total depth of only 18 inches, or to bedrock if it was struck above the 18-inch level. This depth reached fractured parent material on most sampling sites and included the main bulk of the lodgepole pine root zone.

By these sampling methods most of the evaporation losses of soil moisture could be accounted for, but some of the transpiration losses induced by roots lying below 18 inches may have been missed. Since evaporation was likely to be increased and transpiration decreased by timber cutting, the soil-moisture results are probably conservative in estimating the real effects of the treatments.

Immediately after each sample was dug, it was placed in a metal soil can, weighed in the field, and removed to the Fort Collins laboratory where it was oven-dried at 105°–110° C., and reweighed to ascertain its loss of moisture. The resulting set of moisture data gave estimates of the amount of water present in the soil before evaporation and transpiration had begun to draw out any appreciable moisture. Expressed as a percent by weight, this amount may be considered to approximate or perhaps somewhat overestimate the "field capacity" of these soils.

In the autumn, about September 15 to 25 each year, a new series of samples was taken in the same manner, within a radius of 1 to 2 feet of each spring sampling point. These samples, after oven-drying and reweighing, provided estimates of the average autumn water content of the soil on each plot. The autumn deficits were obtained simply by subtracting the average autumn water content per plot from the corresponding average field capacity.

As a part of the laboratory work, each sample was sieved to ascertain its relative content of fine and coarse material (under and over 2 mm. in size).

At this stage in sampling and analysis, all moisture data were expressed in grams of water per 100 grams of oven-dry soil. In order to express them in inches of water contained in an 18-inch soil column, it was necessary to obtain an estimate of the specific weight, or "volume-weight," of the soil on each plot, and to convert the percentage results by the use of these estimates. For this purpose two randomized samples of volume-weight were taken on each plot, each sample consisting of two 1,000-cc. subsamples taken with a 4-inch steel cylinder, with one subsample vertically above the other in the undisturbed vertical wall of an excavated pit (fig. 12). After each sample (composed of the 2 subsamples)

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FIGURE 12.—Each volume-weight soil sample was obtained by driving a 4-inch cylinder into a vertical face of undisturbed soil.

was oven-dried, its volume-weight was calculated and its content of fine material (under 2 mm. in size) obtained by sieving. The resulting two values per plot would give the basis for a relatively weak average volume-weight for each of the 20 plots. Since, however, a voluminous set of data was also available on fines content obtained by means of the auger samples, the volume-weight estimates could be improved by means of double-sampling analysis (*41*). Using all 40 volume-weight samples, a regression equation expressing the relation of volume weight to fines content was calculated.[7] Into this equation was inserted the relatively precise mean fines content for each plot. Finally, the data on average moisture deficits by weight for each plot were converted to inches by the following equation:

$$D_I = \frac{D_w \times 18 \times W_v}{100}$$

[7] With a correlation coefficient of —0.638, on 38 degrees of freedom.

where D_I is the deficit to be calculated, in inches depth in an 18-inch soil column; D_w is the deficit by weight, in percent; and W_v is the volume-weight of the soil.

ANALYSIS OF DATA.—As a result of this field and laboratory work we were able to obtain, for each of the factors under scrutiny except snow evaporation, a reliable average figure for each plot or half-plot and for each year of the investigation. As these factors were sampled by various methods on the same 20 plots, all could be subjected to the same general form of statistical analysis. In general the analysis of each factor had 2 objectives: (1) to obtain a table of average results for each major and minor treatment and each year of a study; and (2) to provide unbiased estimates of experimental error and tests of the real nature, or significance, of treatment effects. In addition, as a part of the analysis the average value for each factor, plot, and year was adjusted wherever possible to remove the effects of any sources of error—extraneous to the treatment effects—which could be isolated by statistical control (*42*).

ACCESSORY INFORMATION.—In addition to the quantitative determination of all these factors which are directly associated with water yield, we made qualitative observations of the influence of timber cutting on watershed conditions, on soil erosion, and on the character and volume of the plant cover occupying the plots. To extend the basis for judgment, we made similar observations on new and old timber-sale areas at a number of places in the lodgepole pine type in Colorado.

RESULTS

In the following pages the results of these detailed experiments show how timber cutting affected each of the individual water-yield components that were studied, and then how all the components may be combined to demonstrate the net effects of timber cutting on the amount of water that became available for stream flow.

INDIVIDUAL COMPONENTS

STORAGE OF SNOW.—For the first of these components, initial storage of water in snow, the results obtained before and after the application of treatments are presented in table 1. As shown in item 1, the average amount of water found before treatment ranged from 6.53 inches on the 4 plots which were to be left uncut, up to 7.05 inches on the 4 plots which were to have a reserve stand of 2,000 board feet of merchantable timber. This trend was observed in both 1938 and 1939. Apparently, therefore, even the sorting of the 20 plots into blocks and the randomization of proposed treatments in each block failed to balance all of the natural variations in snow storage which characterize these plots.

In the analysis of pretreatment snow storage, it was found that the water content of snow at individual sampling points within the plots varied markedly with the density and proximity of the surrounding forest. The smallest quantities were stored under clumps of trees, and the largest quantities in the largest available canopy openings—about 60 feet in diameter (*52*). These observations provide a graphic clue to the probable effect of timber cutting on snow storage, because such treatment would increase the number and size of openings in the forest, and hence it should increase the average amount of stored snow.

TABLE 1.—*Initial snow storage, in inches of water content, as affected by timber cutting*

BY INTENSITIES OF CUTTING (UNIMPROVED HALF-PLOTS)

Item	Merchantable reserve stand per acre[1]				
	11,900 ft. b. m. (uncut)	6,000 ft. b. m.	4,000 ft. b. m.	2,000 ft. b. m.	0 ft. b. m.
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
1. Before cutting, 1938 and 1939	6.53	6.75	6.90	7.05	6.78
2. After year of cutting (1940):					
1941	5.42	6.13	6.68	7.20	7.43
1942	6.00	6.95	7.42	8.18	8.32
1943	9.60	11.00	12.10	13.60	13.45
3. Average after cutting	7.01	8.03	8.73	9.66	9.73
4. Difference due to cutting	.48	1.28	1.83	2.61	2.95
5. Average after cutting, adjusted[2]	7.60	8.41	8.61	9.09	9.59
6. Difference due to cutting, adjusted[2]	0	.81	1.01	1.49	1.99

AVERAGE, ALL HALF-PLOTS

Item	Year			Average	Adjusted average[2]
	1941	1942	1943		
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
Improved half-plots	7.38	8.18	13.52	9.69	9.38
Unimproved half-plots	6.86	7.72	12.54	9.04	8.92
Difference	.52	.46	.98	.65	.46

[1] Cutting left average numbers of merchantable and smaller trees (at least 3.6 inches in diameter) as follows:

Reserve stand (board feet)	*Trees per acre (number)*
0	147
2,000	206
4,000	181
6,000	223

[2] Adjusted to values which would be expected if all half-plots had the same average exposure (compass direction) and had stored the same amounts of snow before treatment.

Such increases were actually found in post-treatment observations, as shown for the major timber-cutting treatments in items 2 and 3, table 1. The removal of merchantable trees had a pronounced effect on the initial storage of water in snow; this effect rises in roughly linear relation to the intensity of timber cutting, with maximum quantities resulting from the heaviest cutting; and it remains strikingly consistent from year to year (*51*). It is believed, however, that these unadjusted results and the differences between results obtained before and after cutting (item 4) may contain some of the inherent variations shown in item 1 as well as the effects of timber cutting and of somewhat greater precipitation during the three winters after the plots were treated. For this reason the observed results were adjusted by the method of covariance analysis (*42*), removing as far as possible the extraneous effects of past performance and average exposure of the individual plots. The adjusted results and differences due to timber cutting (items 5 and 6) show a smaller, but still a real and consistent influence of the major treatments. On the average, heavy timber cutting resulted in a net gain of about 2 inches of water, or about 26 percent, over the amount calculated for the uncut plots.

As compared to the influence of these major treatments, the removal of additional trees in a timber-stand-improvement cutting induced a relatively small gain in water stored in snow (table 1, Average, all half-plots). This gain (averaging 0.46 inch, or about 5 percent after adjustment) was, however, larger than might have been expected by chance, and was quite consistent from year to year.

NET SPRING PRECIPITATION.—Like initial snow storage, the average amount of precipitation reaching the snow and wet soil after the first snow survey and before June 30 showed quite pronounced effects of the major treatments (table 2). Again, the uncut plots showed the smallest average net precipitation, while the largest quantities penetrated the relatively open canopy of the most heavily cut-over areas. And, again, the lighter cutting treatments exhibited intermediate effects, in approximate proportion to the intensity of timber removal. For this factor, however, our measurements were not designed to isolate the effect of timber-stand improvement.

TABLE 2.—*Net precipitation, in inches of water, during spring snow-melt period*[1] *as affected by timber cutting (averages for 4 plots given each treatment)*

Year	Merchantable reserve stand per acre[2]					Gross precipitation
	11,900 ft. b. m. (uncut)	6,000 ft. b. m.	4,000 ft. b. m.	2,000 ft. b. m.	0 ft. b. m.	
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1941	4.77	5.57	6.04	5.95	6.52	7.31
1942	6.48	7.38	7.74	7.70	8.32	9.30
1943	5.93	6.84	7.26	7.18	7.84	8.56
Average	5.73	6.60	7.01	6.94	7.56	8.39

[1] From the first snow survey (Mar. 15 to Apr. 1) until June 30 of each year.
[2] See footnote 1, table 1.

It is interesting to note that the spring snowfall, combined with cold rains in late May and June, contributed a relatively large amount of water to the total net supply. About four-fifths as much water was supplied by this source as by stored winter snow. Also, most of the spring precipitation fell on snow and soil that were already wet from previous snow-melting, so that almost all of it must have been turned into stream flow. This fact has been verified by preliminary analyses of watershed data on precipitation and runoff.

Furthermore, the percentage increases induced by heavy timber cutting were very much alike for both winter snow storage and spring precipitation.

SNOW EVAPORATION.—Although snow storage and subsequent net precipitation were decidedly increased by timber cutting, the influence of this trend on the available supply of water should be offset to some extent by greater rates of evaporation from snow, which are directly affected by the greater exposure of cut-over areas to sun and wind. We cannot say just how large this variable effect may be; but we can make reasonable estimates from available data on snow evaporation. As shown in table 3, the average total amount of evaporation observed on a 500-square-foot pan in an open area was 2.23 inches of water over the whole winter and spring melting season; and almost all of this loss occurred after melting began in the spring. The total loss varied considerably from year to year, and one winter period (1940–41) actually showed a negative figure for evaporation. This discrepancy may be due partly to the recognized errors of rain gages in measuring snowfall—although, in this relatively wind-free area, shielded and unshielded gages gave practically identical results—and partly to sampling errors in measuring the storage of water in snow before melting began. If the second of these factors was dominant in causing the negative discrepancy, the observed figure on spring evaporation in 1941 should be correspondingly too high, and the total for that year should be relatively close to the true evaporation.

TABLE 3.—*Approximate evaporation from stored snow, 1939-43*

Year	Winter evaporation[1]	Spring evaporation[2]	Total evaporation
	Inches	*Inches*	*Inches*
1939–40	0.63	2.15	2.78
1940–41	—.89	2.75	1.86
1941–42	.63	1.75	2.38
1942–43	.58	1.33	1.91
Average	.24	1.99	2.23

[1] From the approximate date of the first permanent snow each year until the beginning of spring snow melting. Winter evaporation was calculated by subtracting the amount of water stored in snow when melting began from total winter precipitation, measured in shielded snow gages.

[2] From the beginning of spring snow melting until disappearance of snow from the evaporation pans.

For the estimation of snow-evaporation losses under the timber-cutting treatments, we took this average annual figure (2.23 inches) as a maximum for open areas; and we assumed that, at the other extreme, practically no evaporation would occur under a hypothetical, completely closed forest canopy.[8] Between these

[8] Twice as dense as the uncut forest, which careful surveys showed to have a canopy density of about 50 percent.

extreme values we could estimate the most probable amount of snow evaporation for each cutting treatment, with the aid of known data on residual stand density and the remaining timber volume of trees larger than 9.5 inches in diameter. As a result 0.80 inch was established as the most likely value for the uncut plots, and 1.40, 1.60, 1.80, and 2.00 inches respectively for the plots containing 6,000, 4,000, 2,000, and 0 board feet of merchantable timber.

MELTING OF SNOW.—The combined effects of initial storage, net spring precipitation, and snow evaporation are integrated in the data on the duration of snow-melt (table 4), which are expressed as the average number of days, each year and for each set of four plots treated alike, between April 1 and the date when the last snow disappeared from each plot. From these figures it was found that no real trend existed before treatment and that timber cutting exerted no appreciable influence on the duration of snow-melt. Both before and after treatment, the last snow disappeared from all the plots during the last week in May and the first week in June; and these dates varied more from year to year than from plot to plot. Their constancy is especially interesting because of the considerable variation in the amounts of snow stored in March of each year after the plots were treated: it means that actually the melting of snow was considerably accelerated on the cut-over areas, but that this acceleration was nicely balanced by the excess quantities of snow which they contained before melting began.

TABLE 4.—*Duration of snow-melt (in days after Apr. 1), as affected by timber cutting*

Year and relation to treatment	Merchantable reserve stand per acre[1]					Average
	11,900 ft. b. m. (uncut)	6,000 ft. b. m.	4,000 ft. b. m.	2,000 ft. b. m.	0 ft. b. m.	
	Days	*Days*	*Days*	*Days*	*Days*	*Days*
Before treatment:						
1938	62.5	63.8	68.5	66.5	65.8	65.4
1939	49.2	53.2	58.5	54.8	56.5	54.4
Average	55.8	58.5	63.5	60.6	61.2	59.9
After treatment:						
1941	50.0	49.8	49.8	51.0	50.7	50.3
1942	57.0	57.8	58.8	61.0	58.0	58.5
1943	54.5	55.0	54.8	56.0	54.2	54.9
Average	53.8	54.2	54.5	56.0	54.3	54.6

[1] See footnote 1, table 1.

NET SUMMER PRECIPITATION.—Like the water content of stored snow and the net spring precipitation, net summer rainfall was strongly influenced by timber cutting (table 5). Stand improvement, however, exerted no measurable effect. These data, adjusted to the same average gross rainfall for all treatments, show that on the average 3.44 inches of water reached the soil under the uncut forest, as compared to 4.63 inches under a heavily cut-over stand. Hence this treatment resulted in an average gain of 1.19 inches, or about 35 percent. Once more, the lighter treatments showed intermediate effects.

TABLE 5.—*Net precipitation, in inches of water, summer and autumn,*[1] *as affected by timber cutting (averages for 4 plots given each treatment), and gross precipitation*

Year	Merchantable reserve stand per acre[2]					Gross precipitation
	11,900 ft. b. m. (uncut)	6,000 ft. b. m.	4,000 ft. b. m.	2,000 ft. b. m.	0 ft. b. m.	
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1941	4.35	5.04	5.37	5.33	5.78	5.89
1942	3.25	3.78	3.99	4.03	4.34	4.65
1943	2.72	3.27	3.46	3.53	3.77	4.13
Average	3.44	4.03	4.27	4.30	4.63	4.89

[1] From July 1 until the autumn soil sampling, about September 15-25.
[2] See footnote 1, table 1.

Stem flow, returning intercepted water along tree trunks to the soil, was found to be of negligible significance. Of a series of 43 storms which yielded 11.3 inches of rain during the summer of 1940, only 9 storms produced stem flow. Assuming an average crown diameter of 10 feet, to place the data on an areal basis, the stem flow per tree totaled less than 0.01 inch of water for the entire set of storms. Hence it was considered unnecessary to add this factor to the data on net precipitation.

AUTUMN SOIL-MOISTURE DEFICITS.—Finally, the timber-cutting treatments showed only a weak average effect upon autumn deficits in soil moisture, and this effect varied considerably from year to year (table 6). Over the 4-year period of study the deficit under the uncut forest averaged 2.19 inches of water; under the most heavily cut-over stands, 1.63 inches. Values for the intermediate treatments were not entirely consistent, but followed the general trend imposed by cutting intensity.

As an informative side light on this phase of the experiments, total summer losses of moisture can be obtained with fair accuracy

TABLE 6.—*Soil-moisture deficits*[1] *as affected by timber cutting, and summer rainfall (in inches of water)*

Year	Merchantable reserve stand per acre[2]					Average	Summer rainfall	
	11,900 ft. b. m. (uncut)	6,000 ft. b. m.	4,000 ft. b. m.	2,000 ft. b. m.	0 ft. b. m.		After July 1	After Aug. 15
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1941	1.53	1.55	1.14	0.86	0.29	1.07	5.89	2.31
1942	2.30	2.58	2.04	2.16	1.98	2.21	4.65	.68
1943	1.86	2.19	1.25	1.86	1.53	1.74	4.13	2.29
1944	3.06	2.61	2.35	2.28	2.71	2.60	2.33	1.09
Average	2.19	2.23	1.70	1.79	1.63	1.91	4.25	1.59

[1] Inches of water required to raise the moisture in an 18-inch soil column to field capacity.
[2] See footnote 1, table 1.

by adding the autumn moisture deficits (table 6) to the net rainfall which reached the ground after July 1 (table 5), on the rather safe assumption that all of this summer rainfall was used by transpiration and evaporation. For neither the individual years nor their average do these sums exhibit a strong trend among the major treatments, indicating that if transpiration was decreased by timber cutting, a compensating increase in evaporation losses must have occurred.

Judging from these observations, the effect of timber cutting on autumn deficits in soil moisture may not result primarily from variations in the sum of transpiration and evaporation from the soil, but more probably depends upon the amounts of net rainfall which reach the soil to replace these losses. After a dry summer season, therefore, the autumn deficits should be much alike under all cutting treatments. After a wet season, on the other hand, when substantially more rain has reached the soil in cut-over stands than in uncut areas, autumn deficits should be more directly and strongly associated with the density of the remaining forest. And obviously late-summer rains should be expected to have the most direct influence in reducing these deficits.

This theory is supported by the experimental evidence. During the wet summer of 1941, 5.89 inches of gross precipitation fell after July 1, including 2.31 inches after August 15; and the autumn soil-moisture deficits showed a very pronounced relation to the timber-cutting treatments (table 6). While all of the deficits were relatively low (averaging 1.07 inches), they varied from only 0.29 inch under the most severely opened canopy, to more than 1.50 inches under the 6,000-foot reserve stand and the uncut forest. In contrast, the summer of 1942 was rather dry; for that autumn, soil-moisture deficits were high (2.21 inches) and there was no significant trend among the cutting treatments. In 1943 the total summer rainfall was low, but 2.29 inches fell after August 15. As a result the autumn deficits were intermediate in amount (averaging 1.74 inches), and there was only a weak trend among the treatments. Finally, in 1944 occurred the lowest summer precipitation in 6 years: the total after July 1 was only 2.33 inches, of which only 1.09 inches fell after August 15. As might be expected, the autumn deficits were exceptionally high (2.60 inches), and they were practically unaffected by timber cutting.

Summation of All Components

In table 7 and figure 13 are presented the average adjusted results for each measured water-yield component and for estimated snow evaporation. These data are shown only for the major timber-cutting treatments, as timber-stand improvement was found to exert only a small influence on snow storage and no perceptible influence on the duration of snow-melt or on net rainfall; and its effect on the other components was not measured.

Unlike the results of earlier studies, all of these components were measured on the same set of plots and over the same period of years; and they include all the most important sources of increment and loss of precipitation on the surface of a forested watershed. Also, the design of the experiment insured that each timber-cutting treatment had an equal chance to express its effect upon these components; and, except in the case of soil-moisture deficits, these effects were consistently found to be larger than might have been expected by chance. Because of these facts, the data on the individual components can be added algebraically, to show the net effect of timber cutting on the amounts of water which became available for stream flow.

TABLE 7.—*Disposition of precipitation as affected by timber cutting*

Factor	Merchantable reserve stand per acre[1]				
	11,900 ft. b. m. (uncut)	6,000 ft. b. m.	4,000 ft. b. m	2,000 ft. b. m.	0 ft. b. m.
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
A. Precipitation reaching the ground:					
1. Snow:					
A. Initial[2]	7.60	8.41	8.61	9.09	9.59
B. Added[3]	5.73	6.60	7.01	6.94	7.56
2. Rain[4]	3.44	4.03	4.27	4.30	4.63
Total	16.77	19.04	19.89	20.33	21.78
B. Losses aside from interception:					
1. Snow[5]	0.80	1.40	1.60	1.80	2.00
2. Rain[6]	3.44	4.03	4.27	4.30	4.63
3. Soil[7]	2.19	2.23	1.70	1.79	1.63
Total	6.43	7.66	7.57	7.89	8.26
Water available for stream flow (net precipitation, minus losses)	10.34	11.38	12.32	12.44	13.52

[1] See footnote 1, table 1.
[2] Adjusted initial snow storage, from table 1 (unimproved half-plots).
[3] Spring precipitation up to June 30, from table 2.
[4] Summer precipitation, July 1–Sept. 20, from table 5.
[5] Estimated evaporation from snow, derived from evaporation-station data.
[6] Same as footnote 3. All summer precipitation reaching the ground after July 1 is assumed to have been lost by evaporation.
[7] Average autumn soil-moisture deficit in an 18-inch soil column, from table 6.

To simplify this table, the various components influencing potential water yield were sorted into two groups: one containing contributions of water to the ground surface (table 7, A), and the other containing the losses of water after it had reached the ground (table 7, B). In approximate terms, the first part is net precipitation, the second is evapo-transpiration losses aside from interception.

When the figures on net snowfall and rainfall are combined, we find that an average of 16.77 inches of water passed through the forest canopy on the uncut plots, and 21.78 inches on the most heavily cut-over areas. The difference represents an increase of 30 percent in net precipitation as a result of heavy cutting. Between these extreme values the lighter treatments gave smaller gains, varying with the intensity of timber cutting.

In addition to the interception losses that are reflected in these

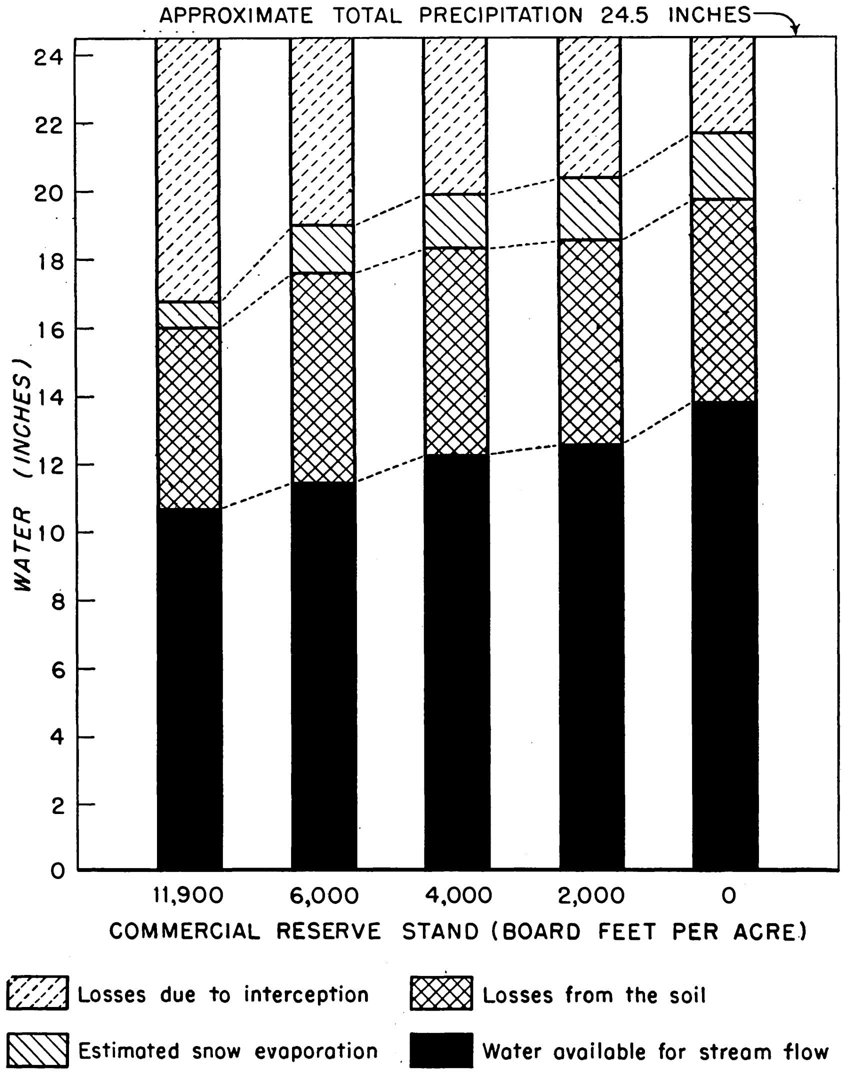

FIGURE 13.—More water is released for stream flow by timber cutting in mature lodgepole pine.

data on net precipitation, the losses due to evaporation from the snow and the combination of evaporation and transpiration from the soil also exhibit quantities which vary with the intensity of treatment (table 7, B, total).

In order to obtain a final estimate of the amounts of water which, passing through the forest canopy and penetrating the soil beyond reach of most roots, became available for stream flow under a forest cover of five different densities, all of the losses shown in section B of table 7 may be subtracted from the average total net precipitation for each treatment. As a result we find that, in the aggregate, 10.34 inches of water become available for stream flow from the uncut forest: about 42 percent of the approximate total annual precipitation. The corresponding quantity for the most heavily cut-over plots was 13.52 inches, or 55 percent of the annual precipitation. For the intermediate treatments smaller gains are indicated, in approximate proportion to the amounts of timber removed.

These findings clearly demonstrate that, on the plots studied, timber cutting exerted a real and substantial influence on the yield of water to the ground-water table, and probably also to stream flow. And the most heavily cut plots yielded the greatest volume of available water.

Effects of Timber Cutting on the Forest and Soil

Aside from its influence on the measured components of water yield, timber cutting exerted a generally small effect on the local environment. Soil stability, for example, was hardly affected: up to the autumn of 1947 no perceptible surface runoff or erosion had been induced, even by the heaviest cutting; and only the steeper skid roads exhibited minor gullies. The surface aspect of the soil did not change except for the addition of quantities of logging debris; and the original forest litter remained on the ground except in skid trails.

Stand regeneration had already started: numerous seedlings of lodgepole pine, spruce, and fir could be found, especially on the heavily cut-over plots. Other vegetation was not yet abundant. New aspen sprouts had appeared on two of the most heavily cut-

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FIGURE 14.—Where strong winds may be expected, heavy cutting of mature lodgepole pine may result in serious losses of timber by windthrow.

over areas, but had not noticeably increased on the other plots. And there had been little invasion of any of the plots by grasses, weeds, or shrubs.

Only one really negative effect of timber cutting was observed. In the spring of 1943, unusually strong winds caused heavy windthrow, particularly in the residual stands on the cut-over plots. The number of thrown trees varied with the intensity of timber cutting; on the average, including scattered trees thrown in previous years, only 4 trees per acre were lost on the uncut plots, as compared to 24 trees per acre in the thinnest reserve stands. Even though such windthrow may occur only at infrequent intervals, the resulting loss is serious from a silvicultural viewpoint (fig. 14).

DISCUSSION AND CONCLUSIONS

Strictly speaking, the results of these experiments apply only to one particular forest of mature lodgepole pine, to the environmental conditions under which the studies were conducted, and to a period of 4 years after treatment. Actually, however, we may have a broader basis for generalization than that indicated by such a rigorous interpretation. First, though the plots were confined within a single small watershed they included a considerable range of exposure, elevation, soil type, and density and quality of forest cover. In spite of these variations, the effect of timber cutting on all but one of the measured water-yield components stood out strongly above the variations in effects which may be charged to environmental factors. Only the autumn soil-moisture deficits showed a substantial amount of variation from one block of plots to another.

Similarly, the effects of timber cutting on all components except the soil-moisture deficits were consistent from year to year as well as from block to block. Thus it may be reasoned that similar effects are likely to occur in future years, at least until the growth of conifer seedlings or other vegetation markedly changes the effective density of the forest canopy. Such a conjecture is supported by examinations of older cut-over areas in the lodgepole pine type, where, except after fire, the regrowth of the forest to normal canopy densities seems usually to require at least 25 years.

As to the influence of timber cutting on the soil and local environment, again the findings are borne out by more widely extended observations. In general, lodgepole pine areas which were heavily cut over from 5 to 20 years ago exhibit no evidence of appreciable erosion, either past or present. Aside from a variable stand of pine seedlings or saplings, they ordinarily contain a sparse cover of weeds, huckleberry, and grasses. Windthrown trees are often found on exposed sites, wherever an appreciable portion of the original stand was left in the cutting operation.

Finally, the results of this study bear out those of earlier investigations conducted in widely separated places and under a variety of environmental conditions. (See pp. 8-12.) In terms of water yield, they are supported by the findings of watershed studies at Wagon Wheel Gap and in North Carolina. Hence it can be safely suggested that these results may be generally applicable to the lodgepole pine type in the central Rocky Mountain region.

Using as background this experiment and investigations by other workers, it is possible to reexamine the water cycle as affected by the forest (pp. 5-6) and to summarize the ways in which this cycle may be influenced in a typical cut-over watershed in the lodgepole pine type. Briefly, timber cutting should increase the net supply of snow and rain and somewhat decrease the autumn deficits in soil moisture, thus providing greater yields of water during the spring peak of stream flow. This peak may be expected to start rising a little earlier and at an accelerated rate, with greater amounts of water derived from snow-melt during the period when discharge is increasing. Ordinarily the water should still pass through the soil rather than form surface runoff, if the watershed has not been severely damaged by the logging operation; for even now the rate of melting should seldom exceed the capacity of the soil mantle to transmit water. Peak rates of stream discharge will probably be increased, though little changed in time; and the subsequent decline in flow should exhibit slight change in time or magnitude until summer, when lessened rainfall interception may cause somewhat higher summer discharge rates. This kind of pattern is quite faithfully presented by the hydrographs obtained before and after treatment of the Wagon Wheel Gap watersheds (*5, fig. 33*).

With the passage of time these pronounced immediate effects of timber cutting will probably be diminished, as the interception of precipitation is increased by the progressive development of a young forest under the old residual stand, or by the invasion of other vegetation. The actual duration of treatment effects can be evaluated only by future measurements.

Even though the cutting of mature lodgepole pine should be generally desirable for the purpose of increasing water yields, the optimum intensity of timber removal must depend on local requirements. In areas of stable soil and where windthrow presents no serious hazard, very heavy cutting may be advisable. On steep slopes or more erodible soil, on the other hand, it may be desirable to leave denser reserve stands for soil protection. In areas of high erosion risk—quite rare in the lodgepole pine type—perhaps no cutting should be permitted. And wherever heavy winds or other causes may destroy a thin reserve stand, the forest should be either clear-cut or perhaps completely protected.

It is strongly emphasized that the results of these experiments by no means justify or even suggest destructive exploitation of forests in the guise of watershed management; but they do show that the amount of water available for stream flow may be substantially increased by carefully managed timber cutting. In any area that is sensitive to erosion or susceptible to floods, increases in water supply resulting from timber cutting may be more than offset by sedimentation and flood damage to both the watershed and water-using lands. In such areas, water production must be subordinated to watershed protection; and on any watershed the dictates of wise land management require that timber cutting be done only with adequate precautions to conserve all watershed resources.

SUMMARY

Of all the natural resources of the central Rocky Mountains, water is the most essential to mankind. Water from their forest-covered slopes is carried into many of the great drainages west of the Mississippi River, and is used for agriculture, industry, recreation, and domestic purposes not only within the Rocky Mountain States, but even far outside their boundaries.

In spite of the apparent abundance of water on the mountains, even the great volumes that flow from these watersheds are not adequate for the full support of present and future human developments. Because of this fact, and because the quantity and quality of water yielded by forest-covered watersheds may be substantially affected by any alterations in the forest cover, experiments have been conducted to ascertain the influence of timber cutting on the amount of water which becomes available for stream flow from a managed forest of lodgepole pine.

THE EXPERIMENTS

Detailed investigations were started in 1938 on a group of twenty 5-acre plots in a forest of mature lodgepole pine near Fraser, Colo. For 2 years records were taken of snow stored on the ground in the uncut forest before melting started each spring; of the length of time required for the snow to melt; and of the amounts of precipitation reaching the soil through the forest canopy. Then, in 1940, 16 of the plots were cut over by selective cutting methods. Since the plots were arranged in 4 randomized blocks, each of 4 cutting treatments and an uncut plot were assigned to each block. All trees larger than 9.5 inches in diameter were removed from one plot; three of the remaining plots were cut over to leave 2,000, 4,000, and 6,000 board feet of merchantable timber per acre; and one plot was left uncut as a check. Supplementing these main treatments, one-half of each cut-over plot was subjected to additional treatment for timber-stand improvement, which removed undesirable trees from the reserve stand.

After treatment several components of water yield were measured over a period of 4 years (1941–44) to show the influence of timber cutting on the disposition of precipitation. Initial snow storage—the water content of snow before any water was released to the soil by melting—was sampled by a survey of all plots about March 15 each year. The progress of melting was then followed by means of repeated weekly surveys, continuing until the snow had disappeared from all the plots. During the snow-melting period and throughout the summer, rain-gage records indicated how much precipitation reached the snow or soil through the forest canopy under each timber-cutting treatment. And finally, detailed records of soil moisture were obtained each autumn to measure the integrated effects of transpiration, evaporation, and precipitation during the summer upon soil-moisture deficits. This last component—deficiencies in moisture below the capacity of the soil to hold water against gravity—is especially important, because such deficits must be replenished by melting snow each spring before any appreciable amount of water can pass through the soil into ground water and thence into streams.

By these methods of study exhaustive records were obtained on all important phenomena involved in the disposition of the precipitation as affected by timber cutting, with the exception of evaporation from the stored snow. While this component could not be measured directly on the plots, records of snow evaporation were obtained from a large stationary pan, and with these data as a base reasonable estimates were made of snow evaporation on the plots.

In addition to these quantitative data on factors associated with water yield, observations were made to show the effect of timber cutting on the forest environment and especially on soil erosion. These were checked and amplified by inspection of recent and older timber-sale areas at a number of places in the lodgepole pine type.

Results and Conclusions

Timber cutting exerted pronounced effects on all the measured components except soil moisture, and these effects increased consistently with the intensity of timber removal. On the average, for example, the initial storage of snow was increased 26 percent by the heaviest timber cutting, and 5 percent by timber-stand improvement.

Regardless of the intensity of cutting, the snow disappeared from all plots at approximately the same time. Actually, however, melting was more rapid on the cut-over plots, as the larger amounts of snow which they contained melted in about the same time as the lesser amounts in the uncut areas.

Like the amounts of water stored in snow, net precipitation reaching the snow and soil varied markedly under the several timber-cutting treatments, although in this case timber-stand improvement exerted no measurable effect. During the spring periods (before July 1 each year) the average amount of net precipitation was increased 32 percent as a result of the heaviest timber cutting; and the corresponding figure for the summer periods was 35 percent.

Autumn soil-moisture deficits were also affected by timber cutting, but to a less pronounced degree than the other factors; and the effects were less consistent from year to year. Apparently the influence of timber cutting on these deficits did not result primarily from variations in water consumption under the several treatments, but depended largely upon the amounts of net rainfall which reached the soil to replenish these losses. After dry summer seasons, for example, the autumn deficits in soil moisture were much alike under all cutting treatments; and the greatest treatment effects were observed after a wet season, when substantially more rain had reached the soil in the cut-over stands than in the uncut areas.

When the various components of net snow storage and rainfall were combined with estimates of snow evaporation and the data on soil-moisture deficits, quantitative figures on the amount of water available for stream flow under each timber-cutting treatment were obtained. On the uncut plots this amount was 10.34

inches, or about 42 percent of the total annual precipitation. In contrast, the heavily cut-over plots yielded 13.52 inches, so that this treatment actually caused an increase of 31 percent in the quantity of water available for stream flow.

As to the effect of timber cutting on the soil, no visible erosion has occurred on any of the plots aside from minor gullying of the steeper logging roads. New seedlings of lodgepole pine and other conifers have appeared on the cut-over areas and a number of aspen sprouts are developing on two plots; but otherwise the surface aspect of the plots has been very little altered. The carpet of forest litter has apparently not changed in condition or appearance, and there has been little invasion by grasses, weeds, or woody plants. Since similar conditions were observed on other cut-over areas, they seem to be rather characteristic of the lodgepole pine type, at least in Colorado.

These experiments definitely show that timber cutting in the lodgepole pine type of the central Rocky Mountains exerts a real and immediate influence on the amount of water available for stream flow from these forested watershed lands. The duration of the influence and its quantitative effect on water yield are as yet undetermined; in this forest type, however, the pronounced reduction in cover density induced by timber cutting should be expected to cause substantial increases in water yield. Unless cut-over areas are invaded by quick-growing aspen, there should be only a relatively slow return to normal canopy densities and interception rates.

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